NACA TN No. 1628

4 JUN 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1628

AN ANALYSIS OF THE VARIATION WITH ALTITUDE OF EFFECTIVE GUST VELOCITY IN CONVECTIVE-TYPE CLOUDS

By H. B. Tolefson

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

Washington
June 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1628

AN ANALYSIS OF THE VARIATION WITH ALTITUDE OF EFFECTIVE GUST VELOCITY IN CONVECTIVE-TYPE CLOUDS

By H. B. Tolefson

SUMMARY

Available gust-velocity data for convective-type clouds at various altitudes are analyzed to determine the variation with altitude of the effective gust velocity. These data include about 1000 miles of record distance at altitudes up to 34,000 feet in the vicinity of Langley Field, Va., and 6700 miles of record distance at altitudes up to 26,000 feet in the vicinity of Orlando, Fla.

The analysis indicates that the distribution of effective gust velocities is roughly equal at various altitudes within convective-type clouds. The number of gusts of a given intensity encountered per flight mile at different altitudes within convective-type clouds would, therefore, be essentially equal. Consideration of these results for altitudes below 34,000 feet indicates that similar results would apply to convective-type clouds within the troposphere at altitudes above 34,000 feet.

INTRODUCTION

The results obtained from routine collections of gust data with the V-G recorder (reference 1) and from special investigations such as those described in reference 2 have provided the basis for specifying the present design gust load requirement of a 30K foot per second effective gust velocity where K is the relative alleviation factor (reference 3). Whereas this requirement has been found to be satisfactory for flight operations up to moderate altitudes, the present trend toward higher operating altitudes has raised the question of the proper gust velocity to be used in the design of high-altitude airplanes. The requirement of reference 3 has been felt to be overly conservative for high-altitude operations so that high-altitude airplanes will suffer a severe weight penalty.

As a tentative solution to the problem of proper selection of design gust velocities at various altitudes, reference 4 proposes the use of a design gust velocity of constant equivalent airspeed for altitudes up to 25,000 feet. For higher altitudes a linear variation with altitude of design gust velocity from the value prescribed for 25,000 feet to 60 percent of that value at 50,000 feet is proposed. The reduction in design gust velocity at altitudes above 25,000 feet in this proposal is based on estimates of the amount of convective-type clouds at various altitudes. These estimates indicate that the amount of rough air and, consequently, the total number of gusts decrease at the higher altitudes. In order to obtain a final solution, more complete information on the gust velocities in rough air as a function of altitude and on the amount of rough air at various altitudes is required.

In the present paper, the variation of effective gust velocity in convective-type clouds with altitude is investigated. Data obtained during 1941 and 1942 at altitudes up to 34,000 feet and data obtained more recently from the Thunderstorm Project (reference 5) at altitudes up to 26,000 feet are utilized for this purpose. Consideration is given in analyzing the results both to data for the range investigated and to extrapolations of the data to higher altitudes.

SCOPE OF DATA

Gust-velocity data for altitudes up to about 34,000 feet were obtained by the NACA from 35 flights in the vicinity of Langley Field, Va., during the spring and summer months of 1941 and 1942 (reference 2). It was intended that successive surveys of cumulus congestus and cumulo-nimbus clouds would be made at decreasing altitudes during the period of maximum convective activity. Frontal activity was of importance as a cause of the turbulence encountered on only a few of the flights. About 12 percent of the total record mileages were taken at altitudes of 30,000 feet or greater; about one-half of the records at these altitudes were taken in thunderstorms, with the remainder taken in cirrus clouds or clear air in the vicinity of the tropopause. A summary of the number of traverses made with the airplane and the distances traveled during recording of gust-velocity data within various altitude ranges is given in table I.

Additional gust-velocity data for altitudes from 6000 feet to 26,000 feet were obtained from operations made during the summer of 1946 of the Thunderstorm Project at Orlando, Fla. (reference 5). These data were taken during simultaneous traverses of a cumulus congestus or a cumulo-nimbus cloud by two to five fighter airplanes at different altitude levels. The clouds were caused primarily by surface heating since frontal activity was present in the vicinity of Orlando on only two of the 38 flight days. The number of traverses and the distances traveled during turbulence recordings at the various altitudes surveyed by the airplanes are summarized in table I.

EVALUATION OF DATA AND RESULTS

The records taken during 1941 and 1942 have been previously evaluated in reference 2 for effective gust velocities by use of the formula:

$$U_e = \frac{2\Delta n W}{\rho_0 a V_e S K}$$

in which

U_e effective gust velocity, feet per second

Δn acceleration increment, g units

W weight of airplane at time acceleration increment was experienced, pounds

ρ_0 air density at sea level, slugs per cubic foot

a slope of lift-coefficient curve corrected for Mach number effect, per radian

V_e equivalent airspeed of airplane, feet per second

S wing area, square feet

K relative alleviation factor taken from figure 9 of reference 3

The results of this evaluation for different ranges of altitude are shown as frequency distributions in table II. The gusts in the lowest altitude range (altitudes from 0 to 5000 ft) of reference 2 were omitted from table II because a relatively small amount of data was obtained at those altitudes. The data in the interval of effective gust velocity from 0 to 4 feet per second were also omitted from table II since all gusts in that interval could not be evaluated, and the data in this interval do not represent a complete count. The average number of miles per gust for each altitude range, obtained by dividing the record distances of table I by the respective total gust frequencies, is also shown in table II.

The records obtained from the Thunderstorm Project were evaluated in a similar manner with the exception that only the maximum positive and negative effective gust velocities above a minimum value of about 4 feet per second for each 3000 feet of each traverse were computed. The gust-velocity distributions given in table III for the Thunderstorm Project are, therefore, not strictly comparable to the distributions for the 1941-42 data but represent distributions of the maximums over short space intervals rather than distributions of all gusts above a 4 foot-per second threshold. The values of miles per gust of tables II and III are not comparable for similar reasons.

In order to smooth out minor irregularities in the data, Pearson type III probability curves were fitted to the frequency distributions of tables II and III by standard statistical methods (reference 6). The curves for the two sets of data are shown in figures 1 and 2. Tests for "goodness of fit" indicate that the curves give a satisfactory representation of the data.

In view of the differences cited in the methods of obtaining the frequency distributions for the two sets of data, the use of the term "probability" with reference to figures 1 and 2 has different meanings. For figure 1, the term probability used herein indicates the relative frequency with which the given values of effective gust velocity will be exceeded within the various altitude ranges. For figure 2, the term probability indicates the ratio of the number of 3000-foot intervals in which a given effective gust velocity will be exceeded to the total number of such intervals at the respective altitudes.

For ease in interpreting the results, the probability curves of figures 1 and 2 have been referred to a mileage scale in the following manner: If P is the relative frequency with which a given value of gust velocity will be exceeded within an altitude range, then that value will be exceeded, on the average, once in 1/P gusts. The average number of miles in rough air that must be flown to encounter a gust equal to or greater than the given value then equals 1/P multiplied by the average number of miles per gust as taken from tables II and III. These results for the various altitude ranges of the two sets of data are shown in figures 3 and 4. This reduction of the data from the Thunderstorm Project does not yield actual mileage values because only a limited number of the largest gusts were evaluated. The values obtained, however, are a measure of the flight miles and may, therefore, be used for making comparisons between the Thunderstorm-Project data for different altitudes. No direct comparison between the Thunderstorm-Project and 1941-42 mileage values can be made.

DISCUSSION

An inspection of figure 1 indicates that the data for altitudes above 10,000 feet form a family of curves distinct from the data below 10,000 feet. This observation is confirmed by application of the Chi-squared test (reference 7) to the frequency distributions of table II, which indicates that no significant differences exist between the distributions for the altitude intervals above 10,000 feet. These distributions, however, are significantly different from the distribution for the altitude interval below 10,000 feet. It may also be seen from figure 1 that variations of only about ±2 feet per second occur between the values of effective gust velocity which would be exceeded at the various altitudes above 10,000 feet for a given probability value. Since these variations are within the range of precision of the effective-gust-velocity computations (reference 2), it would appear that the distribution of gust velocities in convective-type clouds at the various altitudes above 10,000 feet is roughly equal.

The disagreement noted between the data for altitudes above and below 10,000 feet in figure 1 can be accounted for by a consideration of the flight procedure and the test conditions during the 1941-42 investigation. As has been previously indicated, the cloud surveys were usually begun at the higher altitudes with the cloud in its peak stage of development. In some instances where large clouds were being investigated, the available record time was consumed during traverses of the upper parts of the clouds so that no gust velocity measurements were obtained at the lower altitudes within the clouds. In other instances, the cloud under study had dissipated to a considerable extent by the time the lower altitudes were reached and the remaining record time was consumed during flight through small clouds at altitudes below 10,000 feet or in regions of clear air turbulence in the vicinity of these clouds. Hence, because of equipment limitations, the 1941-42 data for altitudes below 10,000 feet were taken under conditions of lower turbulence with a resulting decrease in measured gust intensities.

The probability curves of figure 2 for the data obtained from the Thunderstorm Project form a family of curves similar to those discussed for the 1941-42 data. Tests for significant differences between the data for the various altitudes also indicate no significant differences from 6000 to 26,000 feet. The variation in effective gust velocity between the different altitudes for any probability value is less than ±2 feet per second. These results confirm the findings of the 1941-42 tests that the distribution of gust velocities in convective-type clouds is roughly equal at any altitude within the range of the data.

The preceding results are further illustrated by the mileage curves of figures 3 and 4. It will be noted from figure 3 that when the curve for the altitude interval from 5000 to 10,000 feet is neglected, the variations in the average number of miles in convective-type clouds that must be flown at the different altitudes to encounter a gust equal to or greater than a given value are less than a ratio of 3 to 1. The curve for the lowest altitude interval is neglected because the data are not representative of the conditions surveyed at the higher altitudes. The slight tendency for the mileage values for the altitude interval from 30,000 to 34,000 feet in figure 3 to increase at the higher gust velocities results from the fact that this sample of data includes an appreciable number of miles of flight in clear air and cirrus clouds in the vicinity of the tropopause with only a few large gusts being encountered. Suitable corrections for this effect on the mileage values would probably tend to lower the points for the higher gust velocities so that differences between all curves would be less than a ratio of 2 to 1. Figure 4 also indicates that the differences in the mileages are in the ratio of about 2 to 1. Differences of this order are not considered significant for design purposes.

Since convective-type clouds have been observed to extend to altitudes considerably above the altitude range of the present data, the question of extrapolating the data for clouds at higher altitudes within the troposphere appears pertinent. For any probability value in figures 1 and 2, the scatter in effective gust velocities between the various altitudes has been noted to be only ±2 feet per second, or within the limits of accuracy of the data. This distribution with altitude of points about a line of constant effective gust velocity would indicate that the most suitable extrapolation of the data would be a continuation of the line to the higher altitude.

Further evidence on the question of extrapolation may be obtained by cross-plotting from figures 3 and 4 to determine the variation with altitude of the effective gust velocity for equal miles flown in convective-type clouds. The results are shown in figure 5 for mileages that were selected to include the higher and most critical gusts from airplane design considerations. These results indicate that, for given miles of flight in convective-type clouds, the variation with altitude of effective gust velocity is only about ±2 feet per second when the lowest altitude interval of the 1941-42 data is neglected. The absence of scatter beyond the limits of error of the data together with the linear relationship indicated in figure 5 denote that extrapolation of the data for convective-type clouds within the troposphere would be a straight-line continuation of the constant effective gust velocity.

CONCLUDING REMARKS

Available flight data for altitudes up to 34,000 feet in convective-type clouds indicate that the distributions of effective gust velocities measured at the various altitudes are roughly equal. The gust experience per flight mile within convective-type clouds, therefore, varies to only a small extent at different altitudes. The uniformity of the gust-velocity distributions for the altitude range covered by the tests indicates that these results could be extrapolated above 34,000 feet for convective-type clouds that are within the troposphere.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., March 17, 1948

REFERENCES

1. Rhode, Richard V.: Gust Loads on Airplanes. SAE Jour., vol. 40, no. 3, March 1937, pp. 81-88.

2. Moskovitz, A. I.: XC-35 Gust Research Project - Analysis of Gust Measurements. NACA RB No. L4D22, 1944.

3. Anon.: Airplane Airworthiness. Civil Aero. Manual 04, CAA, U.S. Dept. Commerce, July 1, 1944, sec. 04.2121, p 25.

4. Anon.: Proposed 1947 Edition of Airworthiness (AIR) Standards and Recommended Practices. Doc 3031-AIR/181, vol. III of Final Report of Airworthiness Div., Sec. Session, Prov. Int. Civil Aviation Org. (Montreal, Canada), March 1947, sec. 3.3.1.4.1.

5. Tolefson, Harold B.: Preliminary Analysis of NACA Measurements of Atmospheric Turbulence within a Thunderstorm - U.S. Weather Bureau Thunderstorm Project. NACA TN No. 1233, March 1947.

6. Peiser, A. M., and Wilkerson, M.: A Method of Analysis of V-G Records from Transport Operations. NACA ARR No. L5J04, 1945.

7. Kenney, John F.: Mathematics of Statistics. Pt. II. D. Van Nostrand Co., Inc., 1939, pp. 164-171.

TABLE I

NUMBER OF TRAVERSES AND RECORD MILEAGES

AT VARIOUS ALTITUDES

Altitude	Number of traverses	Record distance (miles)
1941-42 tests		
5,000 to 10,000	89	247
10,000 to 15,000	44	130
15,000 to 20,000	37	180
20,000 to 25,000	21	114
25,000 to 30,000	29	180
30,000 to 34,000	18	117
Totals	238	968
Thunderstorm-Project tests		
6,000	84	1032
11,000	120	1548
16,000	117	1717
21,000	93	1371
26,000	71	1044
Totals	485	6712

NACA

TABLE II

FREQUENCY DISTRIBUTIONS OF EFFECTIVE GUST VELOCITY AND MILES

PER GUST AT VARIOUS ALTITUDES FROM 1941-42 TESTS

	Frequency of gusts					
Altitude (ft) / U_e (fps)	5,000 to 10,000	10,000 to 15,000	15,000 to 20,000	20,000 to 25,000	25,000 to 30,000	30,000 to 34,000
4 to 8	1322	571	760	354	449	215
8 to 12	351	233	335	198	274	161
12 to 16	70	89	129	109	75	51
16 to 20	15	29	48	41	34	17
20 to 24	2	8	15	14	15	7
24 to 28	2	2	5	6	6	4
28 to 32		4	4	1	3	1
32 to 36			1	1		
36 to 40			1			
Totals	1762	936	1298	724	856	456
Miles per gust	.140	.139	.139	.158	.210	.257

TABLE III

FREQUENCY DISTRIBUTIONS OF EFFECTIVE GUST VELOCITY AND MILES PER GUST AT VARIOUS ALTITUDES FROM THUNDERSTORM-PROJECT TESTS

	Frequency of gusts				
Altitude (ft) / U_e (fps)	6,000	11,000	16,000	21,000	26,000
4 to 8	1165	1822	1851	1417	992
8 to 12	535	774	751	621	361
12 to 16	163	286	273	210	145
16 to 20	53	98	121	58	45
20 to 24	15	28	44	26	6
24 to 28	4	9	7	7	4
28 to 32	1	3	4	5	3
32 to 36			1	1	
36 to 40			1		
Totals	1936	3020	3053	2345	1556
Miles per gust	.534	.513	.563	.585	.671

Traverses 84 120 117 93 71

gusts/Traverses 23 25 26 25 22

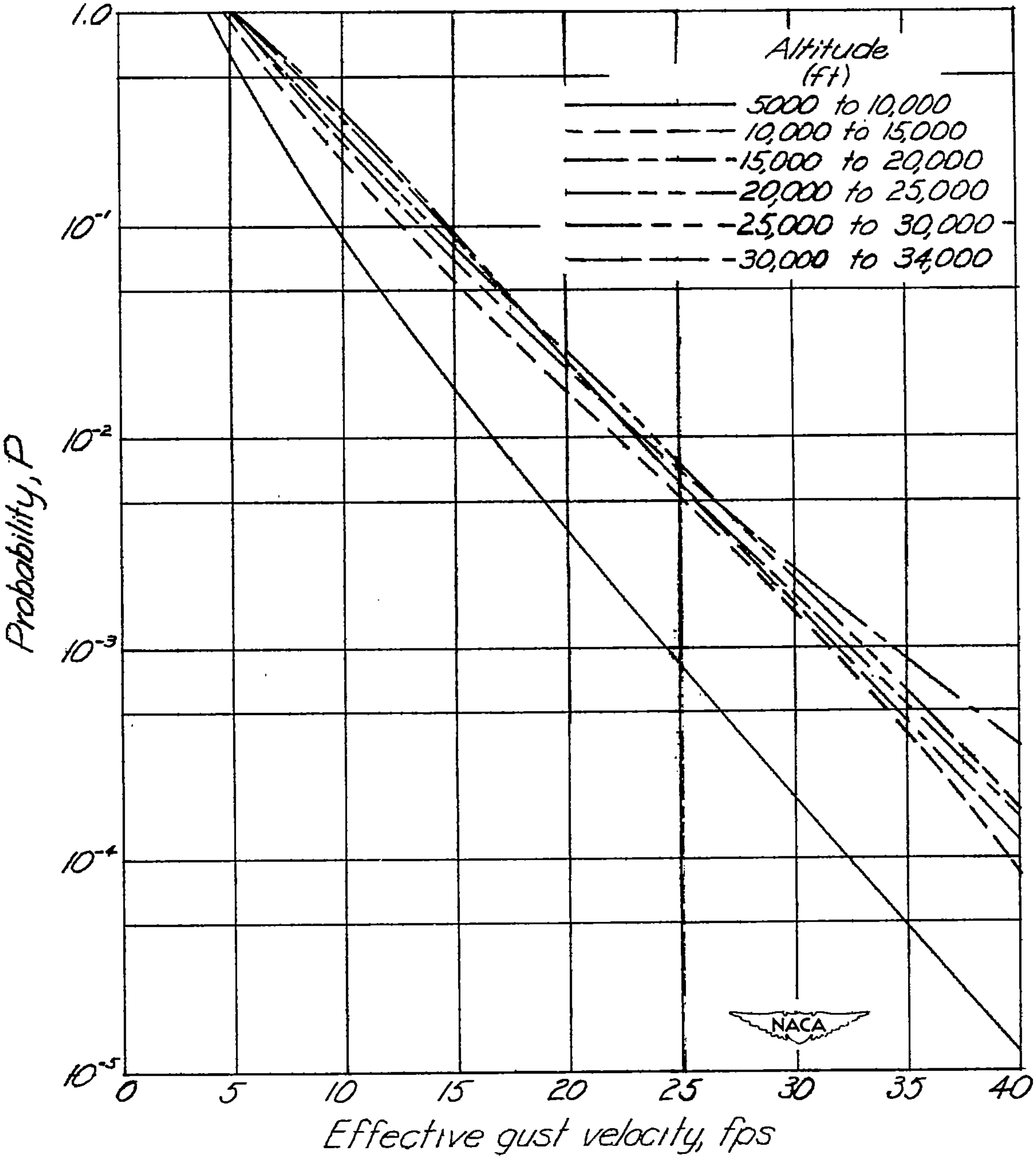

Figure 1.- Probability that an effective gust velocity at various altitudes will exceed a given value. 1941-42 data.

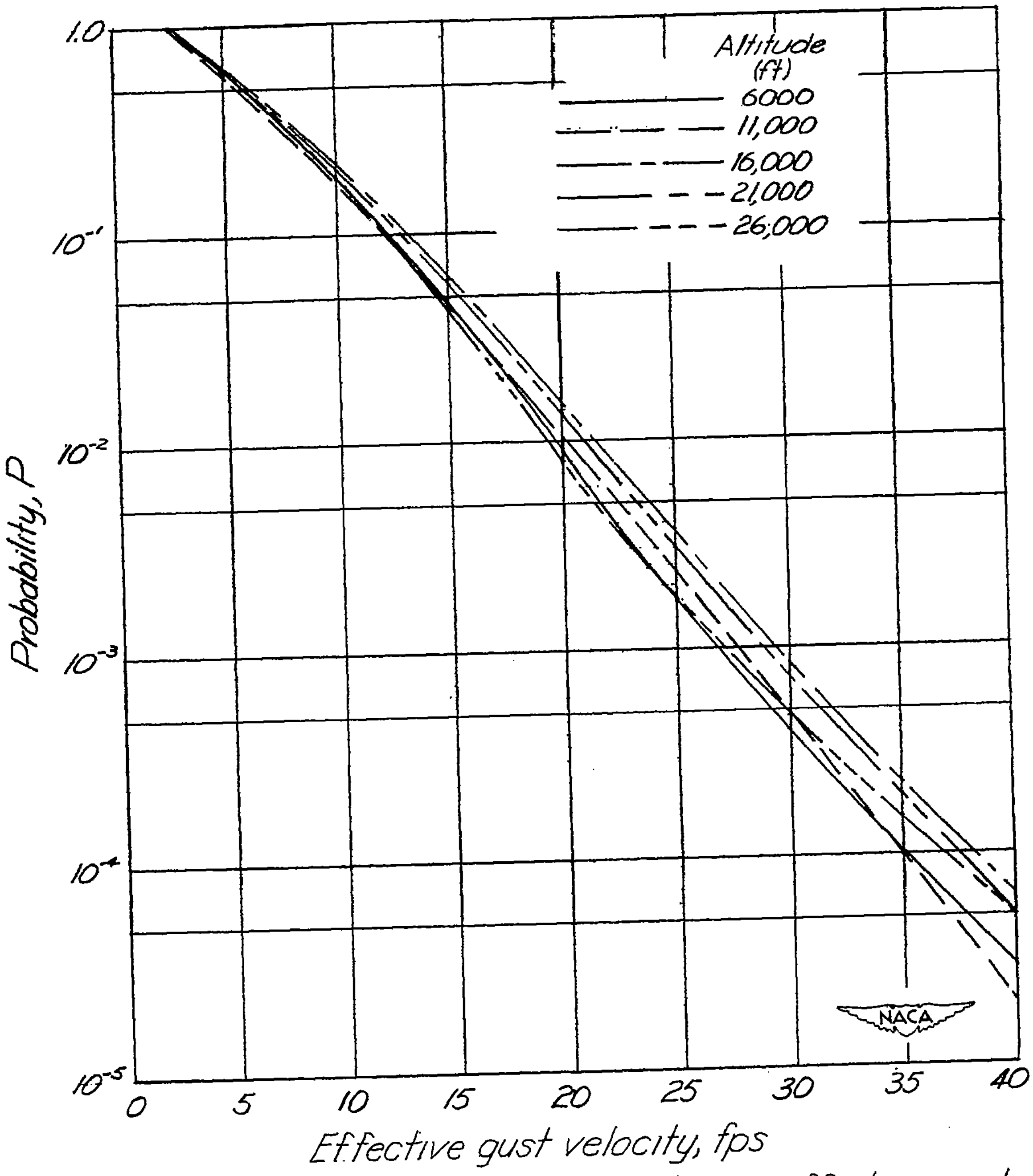

Figure 2.– Probability that the maximum effective gust velocity in a 3000 ft interval will exceed a given value. Thunderstorm–Project data.

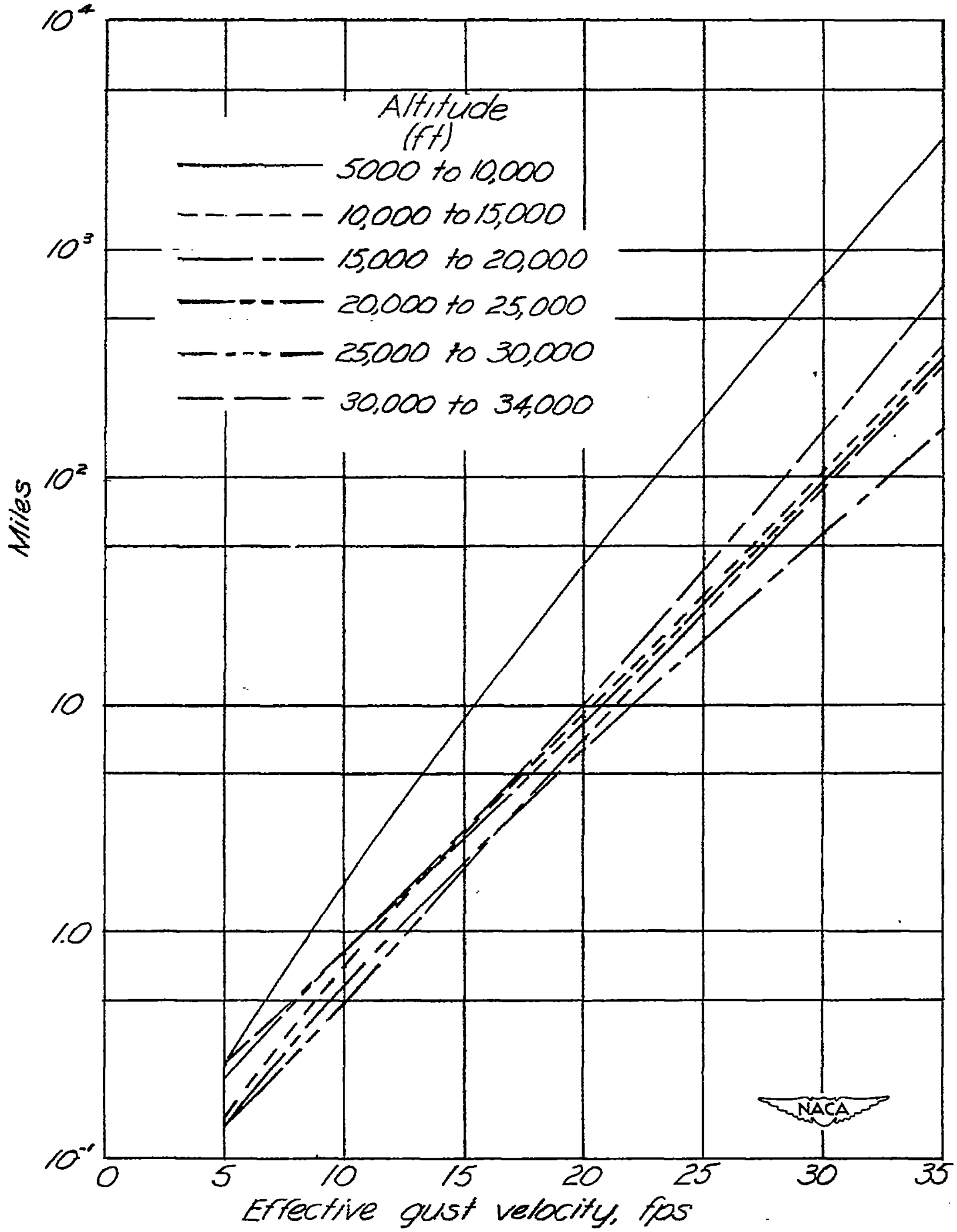

Figure 3.- Average number of miles flown in convective-type clouds to encounter an effective gust velocity equal to or greater than a given value. 1941-42 data.

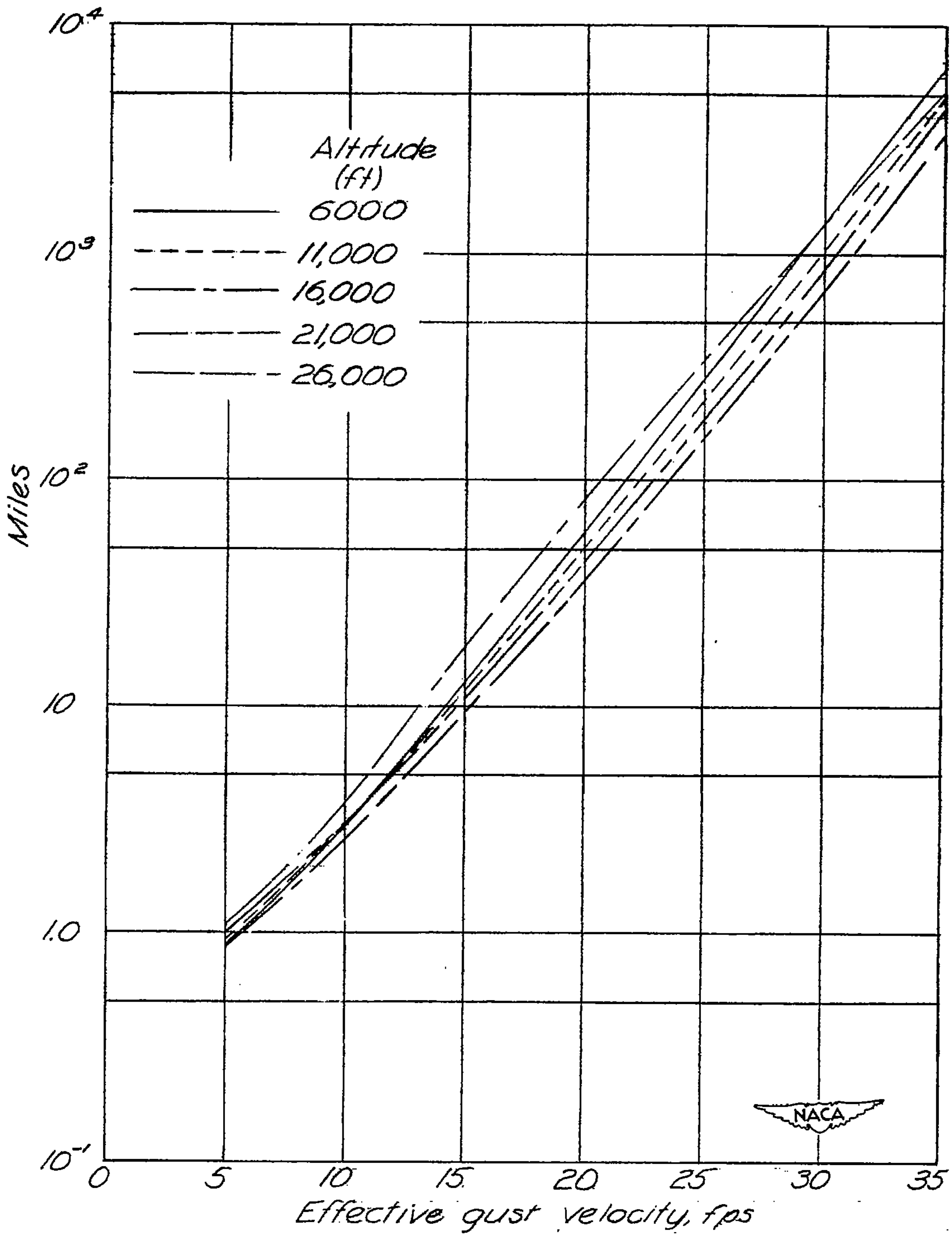

Figure 4.- Average number of miles flown in convective-type clouds to encounter an effective gust velocity equal to or greater than a given value. Thunderstorm — Project data.

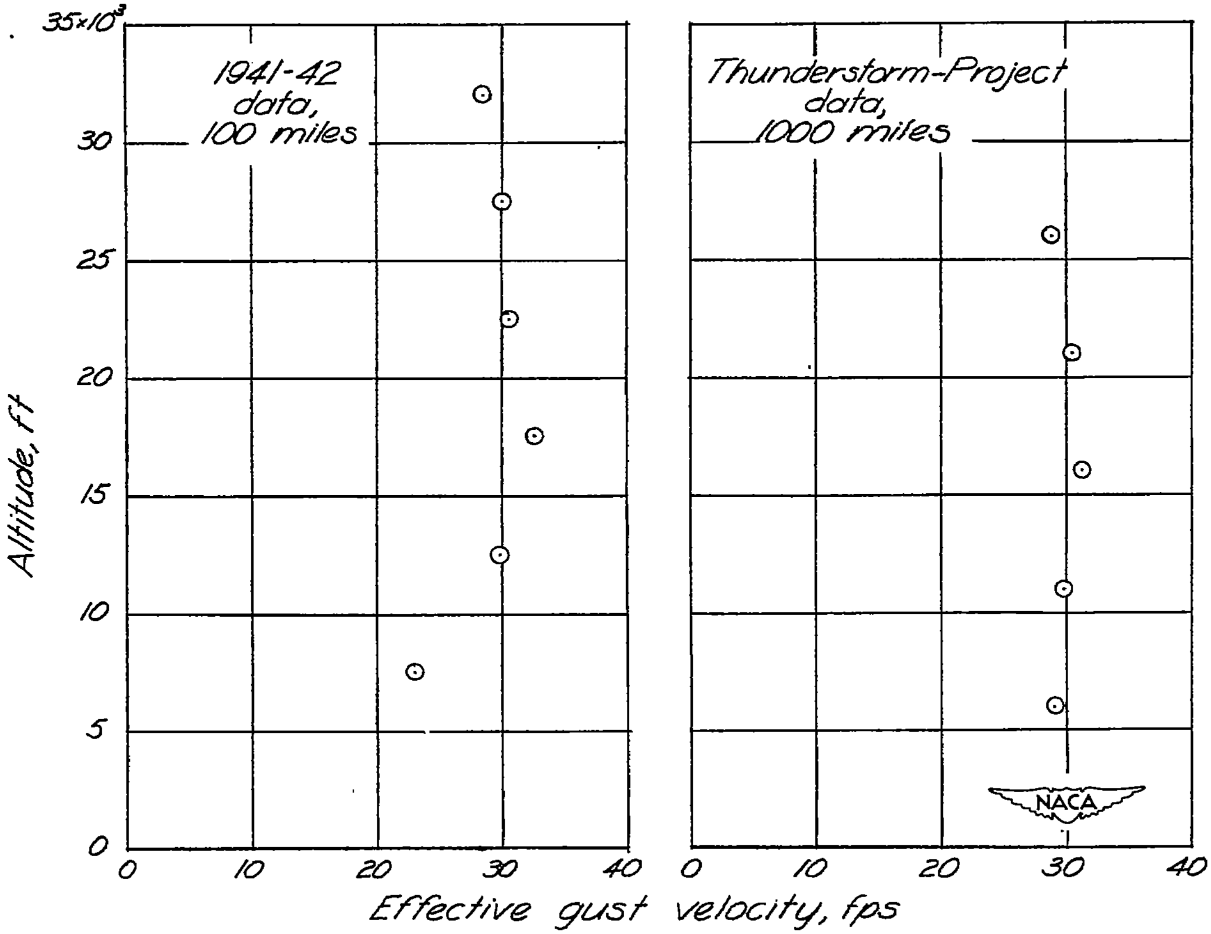

Figure 5.- Effective gust velocity exceeded at various altitudes within convective-type clouds for 100 and 1000 miles of flight from 1941-42 and Thunderstorm-Project data, respectively.